Document Number: SET 2015-0003
412 TW-PA-14282

Evaluation and Analysis of a Multi-Band Transceiver for Next Generation Telemetry Applications

June 2014

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Test Resource Management Center (TRMC)
Test & Evaluation/ Science & Technology (T&E/S&T)
Spectrum Efficient Technology (SET)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
23-02-2015

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*
9/12 -- 9/15

4. TITLE AND SUBTITLE
Evaluation and Analysis of a Multi-Band Transceiver for Next Generation Telemetry Applications

5a. CONTRACT NUMBER:
W900KK-12-C-0048

5b. GRANT NUMBER: N/A

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Morgan State University (INC)
1700 E Cold Spring LN, Baltimore MD 21251-0002

8. PERFORMING ORGANIZATION REPORT NUMBER
412TW-PA-14282

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Test Resource Management Center
Test and Evaluation/ Science and Technology
4800 Mark Center Drive, Suite 07J22
Alexandria, VA 22350

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSOR/MONITOR'S REPORT NUMBER(S) SET 2015-0003

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release A: distribution is unlimited.

13. SUPPLEMENTARY NOTES
CA: Air Force Flight Test Center Edwards AFB CA CC: 012100

14. ABSTRACT
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15. SUBJECT TERMS
Spectrum, Aeronautical telemetry, algorithm, bandwidth, Integrated Networked Enhanced Telemetry (iNET), Shaped Offset Quadrature Phase Shift Keying (SOQPSK), bit error rate (BER), transceiver

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			412 TENG/EN (Tech Pubs)
Unclassified	Unclassified	Unclassified	None	15	**19b. TELEPHONE NUMBER** *(include area code)* 661-277-8615

EVALUATION AND ANALYSIS OF A MULTI-BAND TRANSCIEVER FOR NEXT GENERATION TELEMETRY APPLICATIONS

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ABSTRACT

This paper presents the evaluation and analysis of two multi-band, transceiver architectures that address the current demands in telemetry applications. One architecture used image rejection to perform coarse band selection, translating the RF spectrum to IF frequencies, while the second architecture utilizes an adaptive filter bank architecture for more agile band selectivity. Both architectures consist of an analog front-end subsystem for signal conditioning and frequency translation, and a digital radio subsystem for band and channel selection. The transceiver prototype was designed to operate over the L-band (1435 – 1535 MHz), S-Band (2200 – 2295 MHz, 2310 -2385 MHz), and C-Band (4400 -4950 MHz, 5091 – 5250 MHz). System block-diagrams, simulations and measured results with a comparison between the two architectures, are presented.

The authors would like to thank the Test Resource Management Center (TRMC) Test and Evaluation/Science and Technology (T&E/S&T) Program for their support. This works was funded by the T&E/S&T program through the U.S. Army Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI) contract for W900KK-12-C-0048 for Multi-Band, Multi-Mode Software Defined Radio (MBMM SDR).

I. Introduction

All sectors of the wireless community are challenged to provide its users fast, efficient means of transferring its continually growing volumes of data. The aeronautical telemetry infrastructure is no exception to this challenge. In addition, ns

II. MBMM SDR System Description

The multi-band, multi-mode software defined radio (MBMM SDR) consists of three main subsystems: a multi-band front end with a transmitter (Tx) and receiver (Rx) supporting L/S/C-band telemetry allocations, a digital radio, and a configuration & control sub-system, as illustrated in Figure 1. The multi-band front end (MBFE) provides tri-band operation, band selection, and channel tuning. The digital radio (DR) implements field-programmable gate array (FPGA) technology to provide high-speed signal processing and programmability to support multiple telemetry waveforms. The standard telemetry waveforms to be implemented are pulse code modulation/frequency modulation (PCM/FM) and shaped offset quadrature shift keying (SOQPSK-TG). The configuration and control (C2) sub-system allows for pre-test configuration and control of the multi-band front end and digital radio.

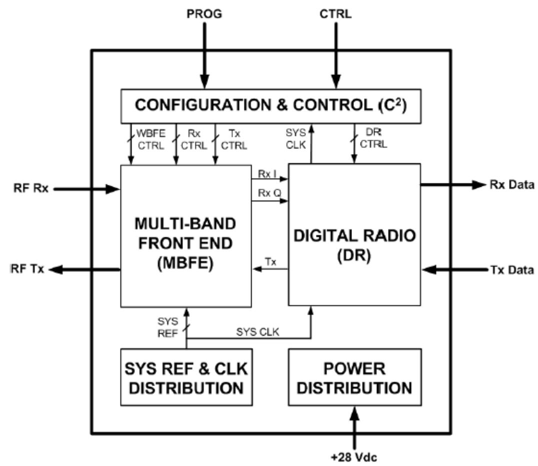


Figure 1: MBMM SDF system diagram.

III. Multi-Band Front End Description, Evaluation & Analysis

The MBFE design consists of three sub-systems: a wideband front end (WBFE), a transmitter (Tx) channel, and a receiver (Rx) channel (channel tuning, CT) as illustrated in Figure 2 and Figure 3 for the respective implementations. Note, each implementation share a common WBFE and adaptable filter bank sub-systems. The implementations differ in the methodology of translating the RF/IF signals. The following general requirements guided the design of each implementation:

- **Tri-Band Operation**
  - The MBFE shall perform with flat gain response across the 500 – 6000 MHz spectrum.
  - Minimum roll off or ripple in the gain response will be tolerated.
- **Band Selection**
  - The MBFE shall possess the ability to select the appropriate spectrum for transmission/reception enabling bi-directional communications.
  - The MBFE shall perform with high selectivity in order to reject adjacent bands and to make the SDR electromagnetic interference (EMI) tolerant.
- **Channel Tuning**
  - The translation section shall possess high port-to-port isolation to minimize unintended transference of interfering signals.
  - The local oscillator (LO) shall possess the appropriate tuning capability to ensure frequency translation of signals within the spectrum of interest.
  - The IF filter response shall be designed such that adjacent channels and interfering signals are attenuated.

Note, the evaluation presented show the capability of the prototypes to meet these general requirements. No attempt was made to ensure compatibility with actual telemetry systems. The design, fabrication and evaluation of such a system are currently under investigation.

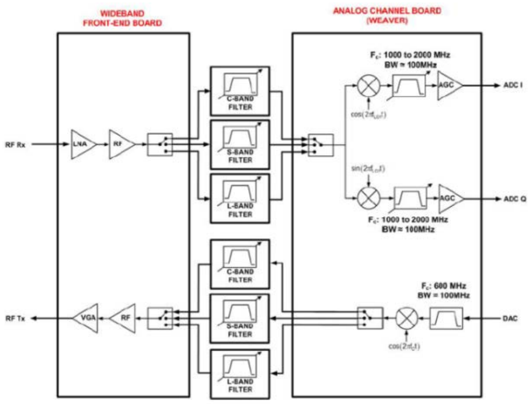


Figure 2: MFBE sub-system incorporating the Weaver implementation.

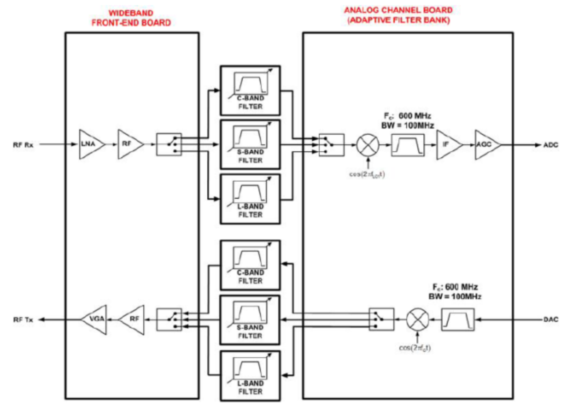


Figure 3: MBFE sub-system incorporating the AFB implementation.

Wideband Front-End (WBFE) Evaluation & Analysis

The WBFE printed circuit board (PCB) sub-system is responsible for providing the tri-band operational capability by conditioning the input RF signals for the Rx channel, and conditioning of the RF output signals for the Tx channel. Evaluation of the WBFE is to ensure that the appropriate signal conditioning (amplification) is achieved within the L/S/C-bands. Figure 4 and Figure 5 present a representation of the gain and return loss (RL) responses for the major amplification sections of the WBFE PCB. The measured responses presented in Figure 4 are representative of the gain and RL performance of both the low noise amplifier (LNA) in the Rx channel and general gain block amplifiers (GBA) in both Tx/Rx channels. Figure 5 presents the measured gain response versus control voltage of the variable gain amplifier (VGA). As seen, the gain response in the LNA/GBA components is fairly flat with less than 2 dB of rolloff. Both the input and output RL responses show good matching capability across the spectrum of interest.

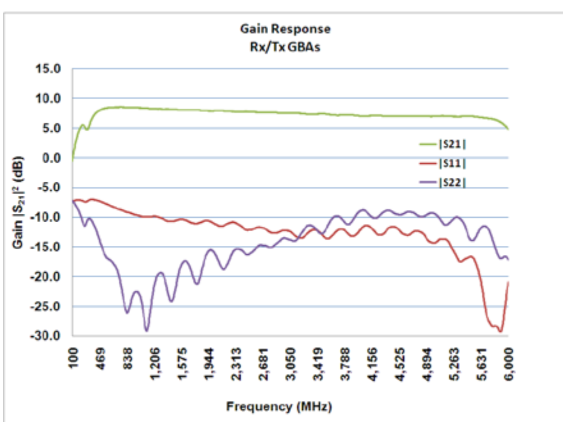


Figure 4: Representative gain and return loss responses for the LNA and GBA in the Rx and Tx channel paths.

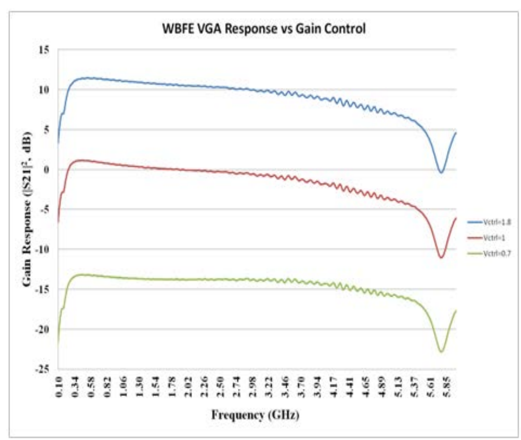


Figure 5: WBFE Tx VGA gain response versus control bias.

The VGA section of the WBFE sub-system is desgined to condition the signal for input to the subsequent power amplifier stage. The control of the VGA enables a range of gain/attenuation to achieve the appropriate conditioning. Figure 5 shows the effective range to be from about -13 dB to +12 dB. Note, significant rollof is seen in the gain performance indicating the need to perform

optimization of this stage of the WBFE in order to flatten the response across the spectrum of interest.

Channel Tuning Evaluation & Analysis: Implementation-Common Sections

Each implementation of the channel tuning sub-system possesses an IF gain stage for signal conditioning and a fixed band pass filter (BPF) for coarse channel selection. The fixed IF BPF is designed with the following characteristics:

- Center Frequency, f_C: 600 MHz
- Pass band Bandwidth: 100 MHz

Figure 5 – Figure 7 present representations of the IF BPF and the cascaded IF BPF/IF Gain responses. The IF BPF and the cascaded responses show excellent selectivity with about 60 dBc between the in-band gain (~35 dB) and out-of-band attenuation (-25 dB min). The selectivity performance will be further evaluated from a spectral perspective later in this report.

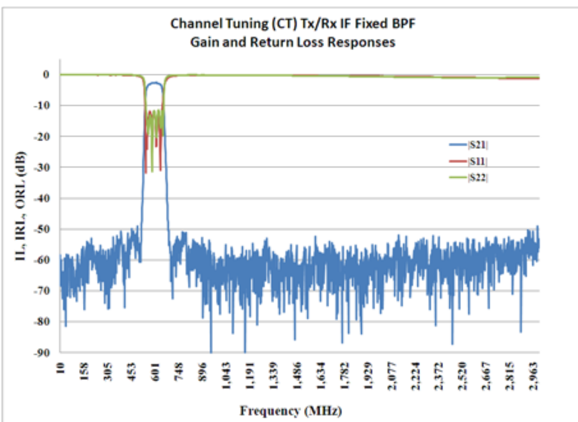


Figure 6: Tx/Rx Fixed IF BPF IL and RL responses.

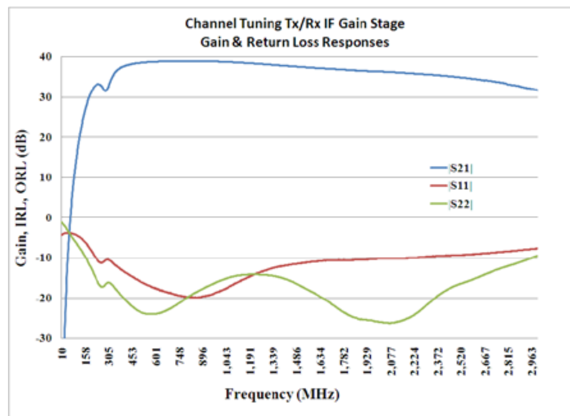


Figure 7: Rx IF amplification gain and RL responses.

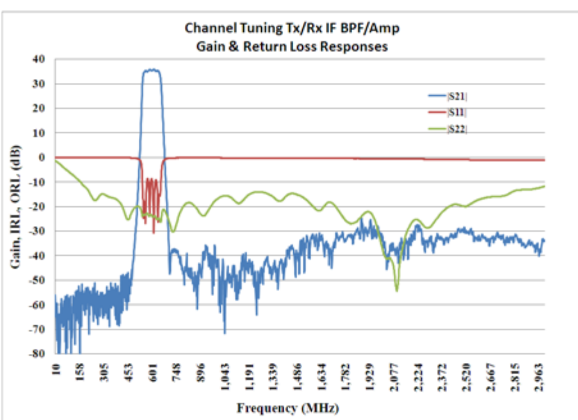


Figure 8: Rx IF BPF/Amp cascaded responses.

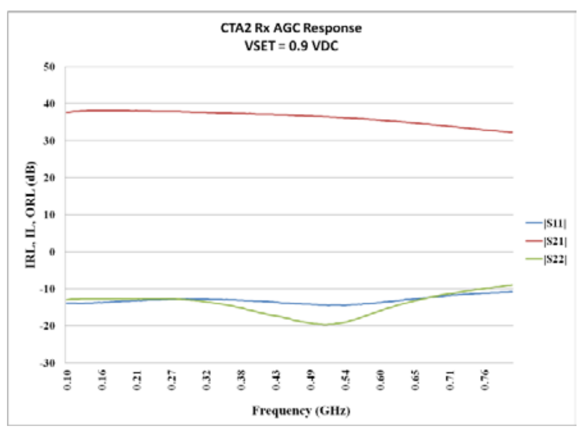


Figure 9: Gain and RL capability of the AGC for an output set point of +10 dBm.

Channel Tuning Evaluation & Analysis: Weaver Rx

The Weaver channel tuning sub-system leverages the image–rejection property to perform band selection between the telemetry allocations. The two-stage frequency translation architecture generates in-phase (I) and quadrature (Q) spectrum components with phase differences relative

to each other. These phase differences allows for the selection between the upper sideband (USB) and the lower sideband (LSB) components. The first frequency translation is performed in the analog domain. The frequency plan for this translation is depicted in Figure 10. This analog stage translates the RF energy to an intermediate frequency equi-distant between the two bands in the respective mode. The evaluation of this sub-system PCB will provide the capability to down-convert the RF energy, to properly capture the IF energy while rejecting potential interferers created by the translation process, and to condition the captured signal for later analog-to-digital (ADC) conversion.

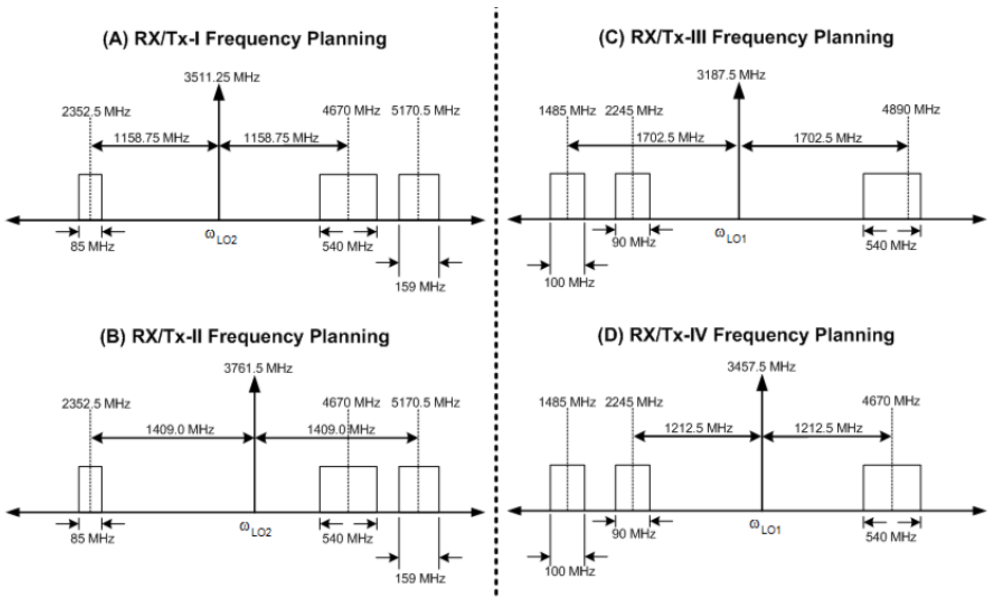
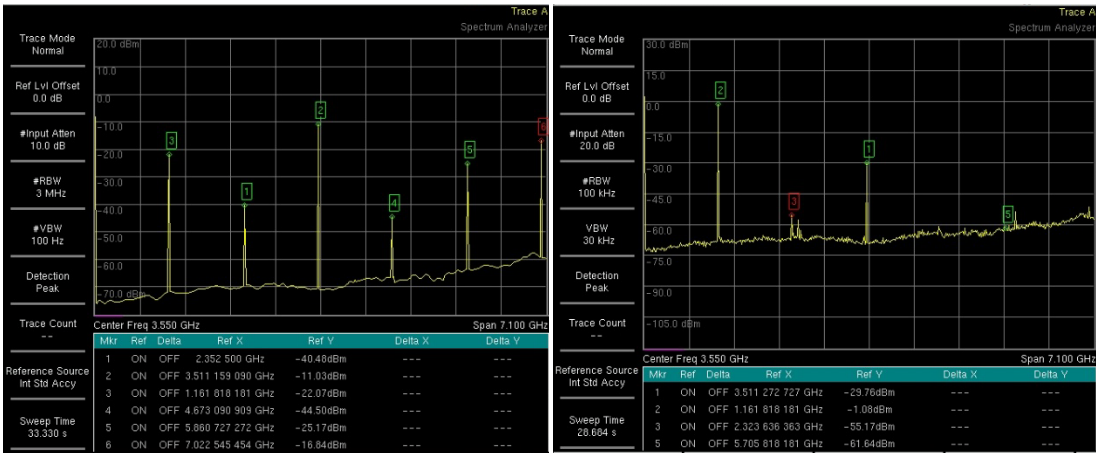


Figure 10: Frequency plan for the Weaver CT implementation.

To evaluate the translation capabilities of the Weaver channel tuning sub-system, the typical metrics for the mixer will be utilized. These metrics include the conversion loss (CL), and the port-to-port isolation ($Isol_{RF\text{-}IF}$ and $Isol_{LO\text{-}IF}$). The output spectrum of the mixer stage is captured using a spectrum analyzer. For each mode, the LO/RF input specifications are given in Table 1. Figure 11a presents the output spectrum for Mode 1. The input specifications and the output spectrum are used to calculate the mixer metrics according to the following:

Table 1: Mixer stage input specifications.

Stage Input	Power Level
$[P_{RF\_in}]_{dB}$	-10 dBm
$[P_{LO\_in}]_{dB}$	+15 dBm



(a) (b)

Figure 11: Spectrum at the output of (a) the mixer stage and (b) the IF ABPF/Amplification stage.

$$CL_{dB} = P_{RF\_dB} - P_{RF\_dB} \qquad \text{Eq. 1}$$

$$\left[P_{RF}\right]_{dB} = \left[P_{RF\_in}\right]_{dB} - \left[L_{\text{int}\_RF}\right]_{dB} \qquad \text{Eq. 2}$$

$$\left[P_{LO}\right]_{dB} = \left[P_{LO\_in}\right]_{dB} - \left[L_{\text{int}\_LO}\right]_{dB} \qquad \text{Eq. 3}$$

$$\left[P_{IF}\right]_{dB} = \left[P_{IF\_in}\right]_{dB} + \left[L_{\text{int}\_IF}\right]_{dB} \qquad \text{Eq. 4}$$

$[P_{XY\_in}]_{dB}$ is the power supplied to the XY port of the mixer stage, $[P_{XY}]_{dB}$ is the power at the mixer's package reference, and $[L_{int\_XY}]_{dB}$ are the internal losses between the stage inputs and the device's package reference.

$$\begin{aligned} \left[Isol_{RF\_IF}\right]_{dB} &= \left[P_{RF}\right]_{dB} - \left[P_{IF\_RF}\right]_{dB} \\ \left[Isol_{LO\_IF}\right]_{dB} &= \left[P_{LO}\right]_{dB} - \left[P_{IF\_LO}\right]_{dB} \end{aligned} \qquad \text{Eq. 5}$$

$[P_{IF\_XY}]_{dB}$ is the power observed at the IF package reference oscillating at the respective XY frequency.

The mixer stage output spectrum is fed into the input of the adaptable bandpass filters (ABPF). The ABPF is configured by supplying two control voltages. The first control voltage defines the center frequency, while the second control voltage defines the the fractional 3dB passband bandwidth. The two control voltages are set in order to center the response of the ABPF at the IF frequency for the respective mode with a bandwidth of approximately 100 MHz. Figure 12 presents the measured ABPF's response for each respective mode of the Weaver implementation.

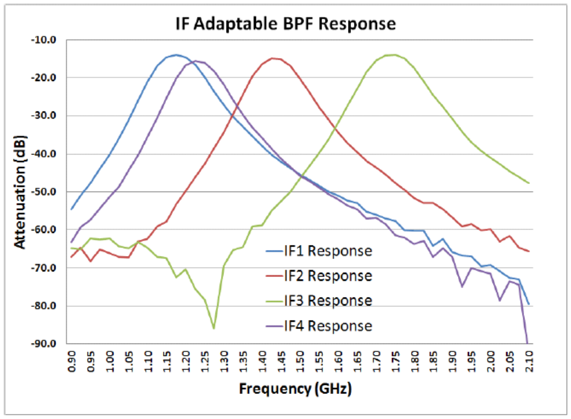


Figure 12: ABPF response for each mode in the Weaver frequency plan.

We define the metric describing the selectivity of the ABPF as follows:

$$Selectivity = [P_{IF}]_{dB} - [P_{XY\_IF\_high}]_{dB} \qquad \text{Eq. 6}$$

$[P_{XY\_IF\_high}]_{dB}$ is the power from the IF port due the highest mixing product or leakage signal remaining after filtering. Table 2 summarizes the mixer metrics and filter selectivity for the four modes of the Weaver implementation.

Table 2: Summary of the mixer metrics and filter selectivity for each mode of the Weaver implementation.

Rx/Tx Mode	Conversion Loss (CL)	RF-IF Isolation	LO-IF Isolation	Selectivity
I	8.6 dB	37 dB	20 dB	28 dBc
II	8.6 dB	40 dB	21 bB	~44 dBc
III	8.7 dB	38 dB	21.7 bB	~37 dBc
IV	8.6	42 dB	21 dB	~30 dBc

Channel Tuning Evaluation & Analysis: Adaptable Filter Bank (AFB) Tx/Rx

The AFB Tx/Rx implementations use a frequency translation stage within the analog channel and the adaptive filter bank sections, which translates a signal at the IF/RF frequency to a pre-selected telemetry band/IF band, respectively. The frequency translation strategy for the AFB Tx/Rx channels is guided by the frequency plan presented in Figure 15. Similar to the evaluation presented for the Weaver implementation, this section summarizes, in Table 3, the capabilities of the AFB Tx/Rx prototypes' to correctly translate the IF/RF signal and capture or band-select the appropriate spectrum.

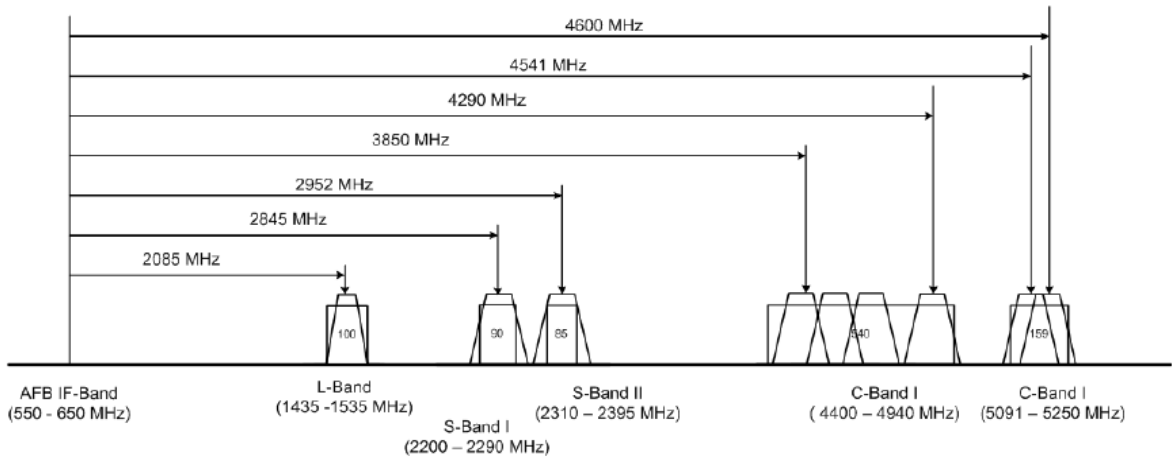


Figure 13: Frequency plan for the translation stages in the AFB Tx/Rx implementations

Table 3: Summary of the AFB Tx/Rx translation and spectrum selectivity capability.

Rx/Tx Mode	Conversion Loss (CL)	RF-IF Isolation	LO-IF Isolation	Selectivity
AFB Tx L-Band	8.6 dB	37 dB	20 dB	45 dBc
AFB Tx S-Band	8.6 dB	40 dB	21 bB	~44 dBc
AFB Tx C-Band	8.7 dB	38 dB	21.7 bB	~45 dBc
AFB Tx L-Band	8.6	30 dB	21 dB	~30 dBc
AFB Rx S-Band	8.7 dB	35 dB	23dB	26 dBc
AFB Rx C-Band	8.7 dB	25 dB	26 dB	19dBc

IV. Digital Radio Description, Evaluation & Analysis

The digital radio firmware supports the transmitter and the receiver chain for both the Weaver and Adaptive Filter Bank architectures mentioned above. For the transmitter chain, the design includes an inverse sinc compensation filter, interpolation stages, baseband-to-IF translation via Nyquist zone replica and mixing, and data conversion to the analog domain.

The Rx digital chain incorporates data conversion using IF under sampling, band selective filtering, baseband translation with fine selection of channel of interest, and the back-end digital receiver which consists of demodulation, synchronization and detection. Figure 14 and Figure 15 FB Digital Firmware Architecture

show the block diagrams for the Weaver and Adaptive Filter Bank (AFB) digital firmware architectures.

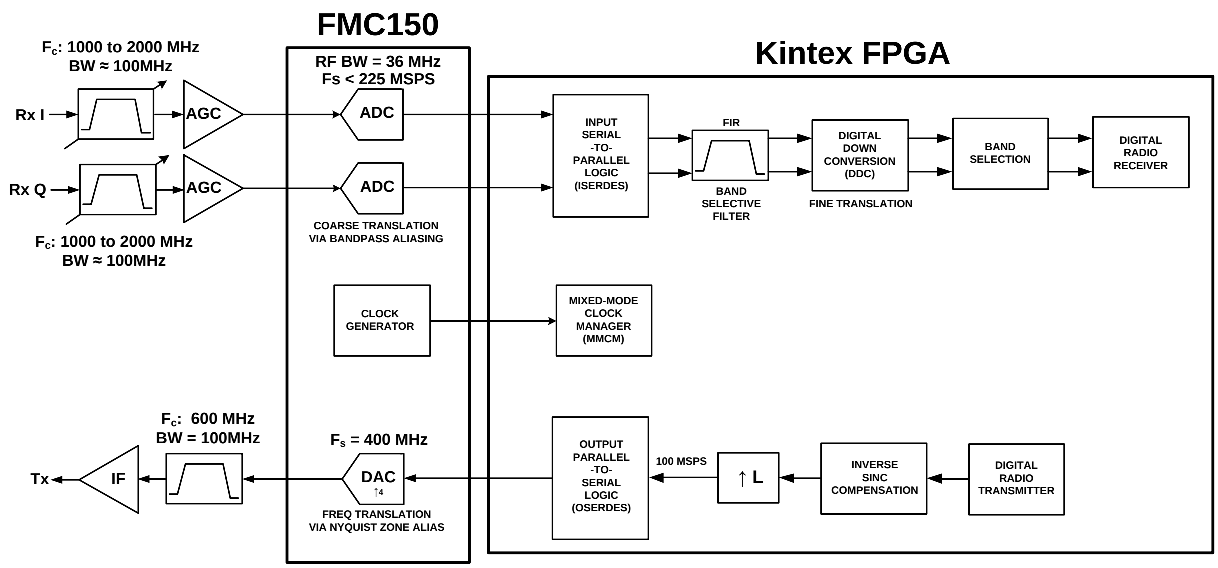


Figure 14: Weaver Digital Firmware Architecture

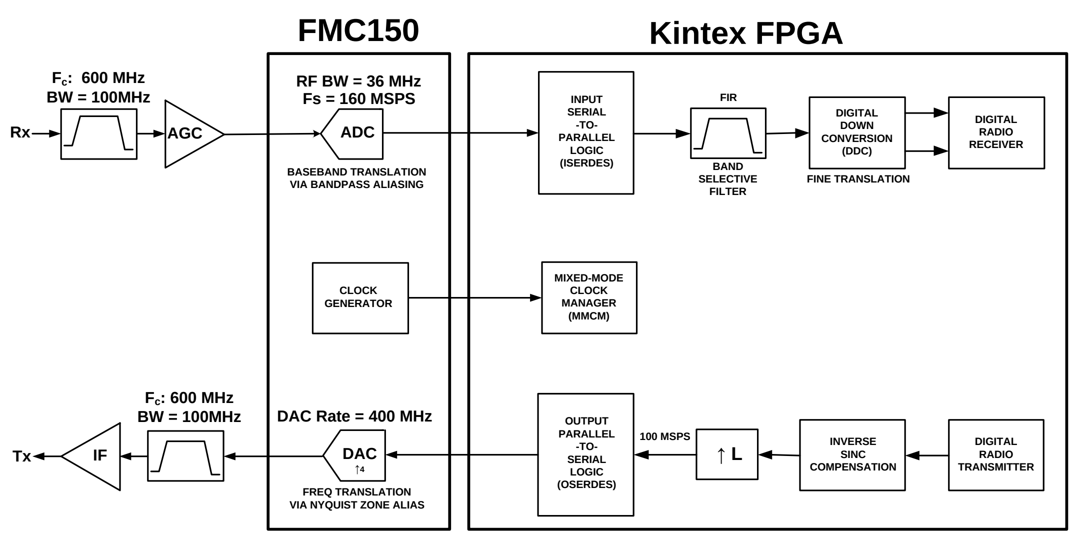


Figure 15: AFB Digital Firmware Architecture

As shown in both figures, the digital firmware interface to the RF analog circuitry is accomplished through an FMC 150 card. The card has dual ADC and DAC chips that are available for quadrature signal processing. The AFB Rx chain uses only one ADC as the signal received from the corresponding analog circuitry is real; the Weaver Rx chain uses both ADCs. The functionalities involved in the Rx chain include coarse band translation, specific channel selection and tuning, and the digital radio back-end for demodulation and detection.

Tx Chain: On the transmitter chain, both architectures incorporate digital waveform generation, an inverse-sync compensation, interpolation stages for rate matching, and final conversion from

digital to analog. Baseband-to-IF translation is accomplished via a Nyquist zone replica that is created during the conversion process.

A frequency translation scheme was devised where the 2nd Nyquist zone replicas from the digital-to-analog converter (DAC) was chosen to serve as the IF input to the analog channel board. A 600-MHz IF signal was selected to relax the analog filter requirements. To ensure that the digital signal would translate to 600 MHz, the DAC rate and ADC rate were configured to be 400 MHz and 225 MSPS, respectively. The frequency translation of the baseband signal to 600-MHz IF is demonstrated in Figure 16.

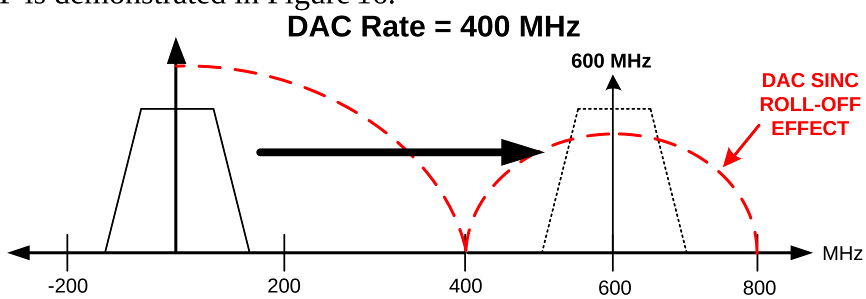


Figure 16: Tx Chain Digital Frequency Translation

Several Tx digital chain configurations are implemented with a chain of FIR interpolation filters. The data rates to be supported are1Mbps, 5Mbps, 10 Mbps, & 25 Mbps. Each configuration mode consists of an inverse sinc compensation stage for compensating the DAC sinc roll-off effect. The interpolation filter types consist of half-band and 5x FIR interpolators. Note, a 4x interpolation stage is implemented within the DAC for each Tx chain configuration mode. shows an example of a 10 Mbps signal conversion to effectively have an output sample rate of 100 MSPS before the DAC interpolation stage.

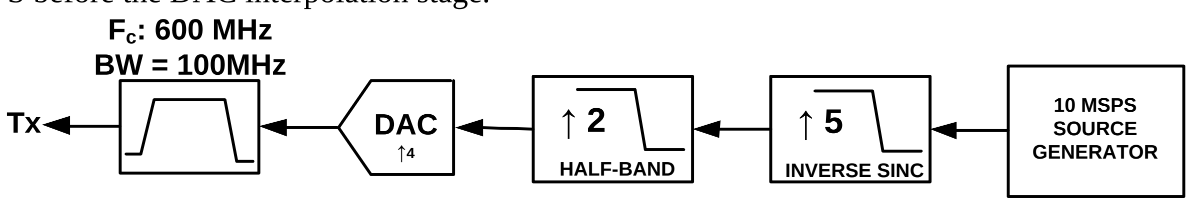


Figure 17: Tx Digital Chain Configuration for 10 Mbps Transmission

Rx Chain: The IF frequencies proposed for both the Weaver & AFB architectures are stated in the IF frequency translation plan outlined below in Figure 18. Since direct Nyquist sampling is not practical at the proposed IF frequencies, band pass sampling is used both for the Weaver and AFB Rx chain. Based on the 100-MHz IF bandwidth specification, the minimum sampling clock is 400 MHz to ensure a minimum availability of 4 samples in every symbol received. This also has the effect of relaxing filtering requirements in the digital domain, since the digital spectrum of any signal converted would span at maximum only 1/4 of the Nyquist zone. In addition, the sampling rate configurations showed in Figure 18 map the sampled signals to the center of the Nyquist zone, which corresponds to 0.25 Cycles/Sample in the digital spectrum.

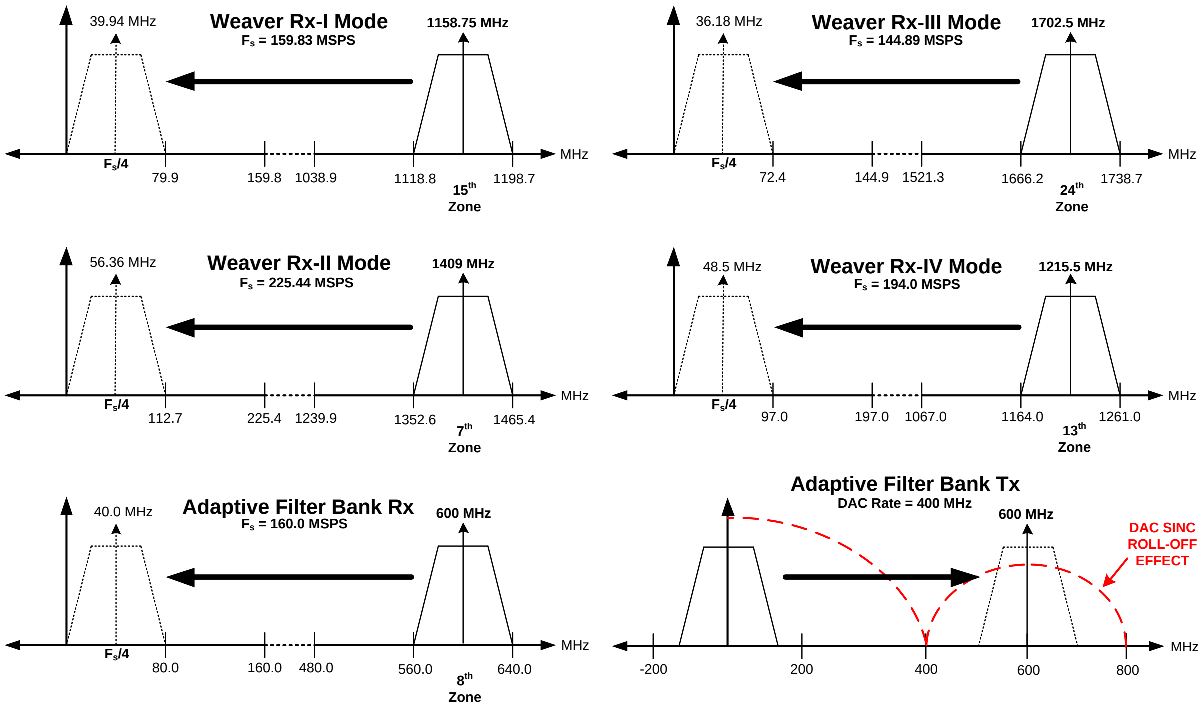


Figure 18: Frequency Translation & Data Conversion to Digital Domain for Weaver & AFB Architectures

Because band-pass sampling can map unwanted signals outside the IF band of interest to within the Nyquist zone, a band selective filter is implemented to filter out any unwanted spectra that does not map into the pass band of the band selective filer. This FIR filter is available for both the Weaver and AFB Rx digital chains. The filter spans a 100 MHz 3-dB bandwidth, and a minimum of 40 dB attenuation in the stop band.

The location of the spectrum of interest from IF at the center of the digital Nyquist zone allows for a down conversion of the spectrum to baseband without an actual heterodyne. The values of for the complex heterodyne -0.25 cycles/sample are limited between +1, 0, or -1, depending whether it's the real or imaginary component. Thus, no complex mixing is required to translate the digitized spectrum to baseband.

RESULTS

Band Selection: For the first phase of the work, the weaver architecture was examined for its performance in being able to band & channel select. Two frequencies of transmission were used at 1485 MHz (designated from here on forth as L-Band signal), and 4489 MHz (designated from here on forth as C-Band signal) at the transmission. Two types of waveforms were used for testing purposes: a continuous wave with peak power of 5 dBm and, a CPM signal at 4

MSymbol/sec. Both signals were produced from an arbitrary waveform generator, which went through a connectorized RF circuitry to form the first stage RF down conversion.

The signal spectrum located at the IF had leakage. As an example, Figure XXA shows the spectrum of the continuous wave signal transmitted at 1485 MHz at an IF frequency of 1702 MHz with the leakage signal present 40 dB below the IF signal. This leakage ended up as a spur within the sampled digital spectrum at 20 MHz and 50 MHz (1st & 3rd) harmonics. In addition, though small compared to the other spurs in-band, the jitter from the external clock used for the ADC sampling showed up as a spur at DC (Figure 21).

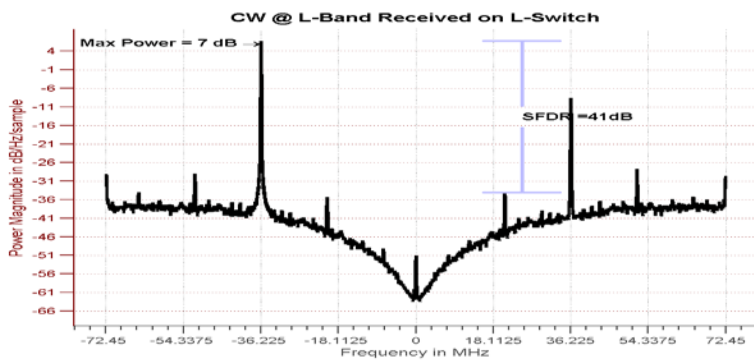
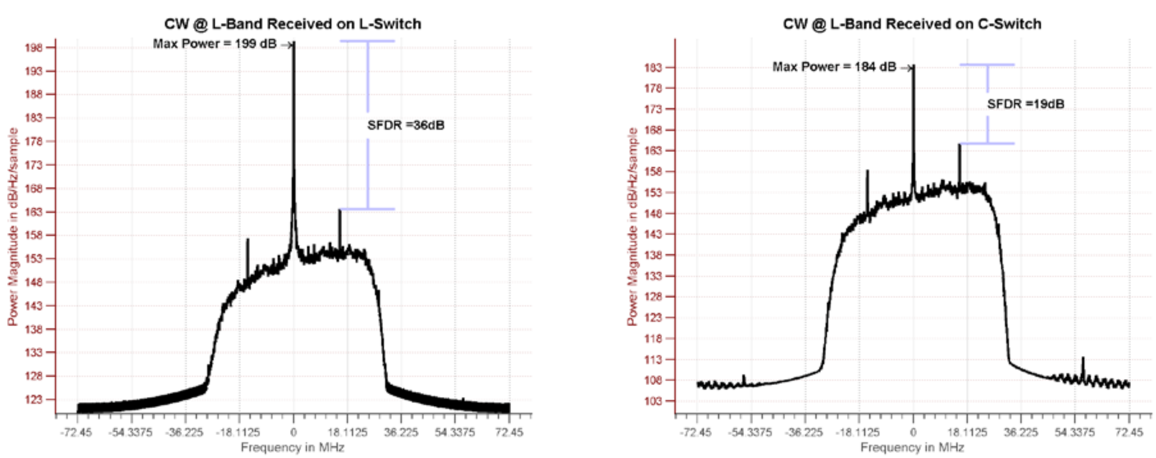


Figure 19: Sepctrum of CW tone after sampling

Digital Image Rejection Performance: To determine the image rejection performance, the spectrum plots between the upper side band and the lower side band spectrum from the digital Weaver channel Rx chain output were compared.

The first evaluation was based on the transmission of an L-Band tone where the lower side band (LSB) component from toggling the L-Switch was compared to the upper side band (USB) component (C-Switch). The resulting spectra from the test are shown on Figure 22 below.



(a) (b)

Figure 20:Transmitted L-Band Spectrum Received on the (a) LSB side & (b) USB, of the Weaver Architecture

As shown in Figure 22, the suppression of the image signal, in this case the L-Switch spectrum, was close to 15 dB(36-19 = 15 dB).

A similar test conducted on a C-Band tone signal received on the C-Switch (USB) was toggled and conversely, the L-Switch was toggled (LSB). The resulting power spectral density plots for the above test showed a 12 dB image rejection between the LSB (image) and USB(desired) signal. Further tests conducted with the Weaver image rejection architecture achieved at least a 10 dB for the CPM signal transmitted for all telemetry bands.

The tests conducted above displayed an I-Q imbalance, as the plot from Figure 22 indicate. This imbalance degraded the image-reject performance of the Weaver Rx architecture since perfect quadrature relationships couldn't be established between the I & Q paths. Still, a 10 dB suppression was achieved. Another factor that degraded the performance of the Rx Weaver channel was the FMC150. Though the daughter card was able to sample the signal, the full bandwidth specification for the card was limited to 500 MHz. This meant that at input frequencies of 1GHz and above, the sampler was not able to optimally capture the analog signal. Thus a better conversion card is needed for optimum operation.

V. Conclusion

As summarized below, the MBFE met the general functional requirements.

- Wideband Operation: 1 to 6 GHz
- Band Selection: Weaver & AFB
- Channel Tuning

In addition to validating the three specific areas, efforts were conducted to distinguish the two implementations (Weaver and AFB). Below are the summary findings of the Weaver vs. AFB comparison:

- I&Q balance mitigation circuitry is required for the Weaver implementation
- AFB is impacted by selectivity due to the fractional bandwidth performance of ABPF at higher frequencies.

As discussed previously, the sub-optimum performance of the FMC 150 has led to re-configuring the design with an FMC 110 card that is capable of supporting the IF frequency and the 100 MHz bandwidth. For the future, this modification for the design will still be able to support both architectures, albeit with minor modifications in the data conversion and frequency planning for IF to digital signal conversion process.